



LITERATURE REVIEW

A Critical Review of Advances in Mechanical Cotton Recycling for Sustainable Denim: Strategies to Overcome Fibre Quality Degradation

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ABSTRACT

PURPOSE: This critical review examines the challenges of fibre quality degradation in mechanical cotton recycling for sustainable denim and highlights strategies to advance a circular textile industry.

DESIGN/METHODOLOGY/APPROACH: A comprehensive review of recent literature and industrial trials was conducted, focusing on optimised blending, chemical innovations, and process improvements. The review integrates technical advancements with industry initiatives to present an holistic roadmap.

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FINDINGS: The main challenge is fibre quality loss (length and strength) during recycling. Solutions require optimising pre-processing, applying quality-driven blending (with virgin or recycled Polyethylene Terephthalate (rPET) fibres), and adopting short-fibre-tolerant yarn technologies such as core-spun, rotor, and air-jet spinning. These methods enable up to 75% recycled content without compromising yarn performance.

ORIGINALITY/VALUE: This paper provides a timely overview of post-2023 developments, shifting the focus from downcycling to process- and design-based upcycling, offering a roadmap for circular denim production.

IMPLICATIONS: While limited to mechanical recycling, true circularity requires fibre-to-fibre pathways and advanced sorting. The review provides practical guidance for manufacturers to incorporate sustainability into mainstream denim Stock Keeping Units (SKUs), supporting sustainability goals and advancing the circular economy.

KEYWORDS: *Mechanical Cotton Recycling; Fibre Quality Degradation; Sustainable Denim; Textile Recycling Strategies; Circular Economy.*

INTRODUCTION

The global denim industry, which produces over 4 billion garments annually, exerts significant environmental pressure due to its intensive use of water, energy, and chemicals. Traditional denim manufacturing consumes approximately 10,800 m³ of water and emits 23.2 tonnes of CO₂ per tonne of denim produced (Li *et al.*, 2025). The global textile industry is a major contributor to environmental pollution, with cotton cultivation being particularly resource-intensive. Producing a single kilogram of cotton fibre can require up to 10,000 litres of water, alongside extensive use of pesticides and fertilisers that contribute to soil and water contamination (Anas *et al.*, 2025; Zhang *et al.*, 2023). The rapid pace of fashion consumption further exacerbates the problem, leading to an annual generation of 92 million tonnes of textile waste, much of which ends up in landfills (Broega *et al.*, 2017). This waste, mainly from cotton textiles, decomposes slowly and can release harmful substances into the environment.

To address these environmental concerns, textile recycling has emerged as a critical strategy for fostering a circular economy. Among various recycling methods, mechanical recycling stands out for its environmental friendliness and cost-effectiveness, as it avoids the use of harsh chemicals associated with chemical recycling (Karmakar *et al.*, 2025). Mechanical recycling involves physically breaking down textile waste into fibres that can then be re-spun into new yarns. This process is particularly relevant for denim, a widely consumed cotton-based fabric. However, a significant challenge in mechanical cotton recycling is fibre quality degradation; this limits the end-use applications of recycled materials.

Mechanical recycling of cotton for denim has surged from pilot initiatives to scaled programmes, but the central technical bottleneck remains fibre quality degradation, principally loss of length, fineness uniformity, and strength during opening/tearing and shredding. Recent reviews and techno-assessments converge on the same mechanism: intense mechanical actions elevate short-fibre content and damage surface integrity; this cascades into lower yarn strength, higher irregularity, and weaving/finishing disruptions. Consequently, the most robust progress since 2023 focuses on (i) pre-processing and tearing-line optimisation to curb damage, (ii) smarter fibre sorting and blending, and (iii) yarn/structure engineering that accommodates shorter fibres without sacrificing denim performance (Islam *et al.*, 2025; Baloyi *et al.*, 2024).

On the process side, industrial “Denim Deal” field interviews and trials recommend fabric lubrication before shredding, lower tearing and spinning speeds, and higher twist, all of which measurably improve yarn integrity when recycled content rises; thicker yarns and tighter weaves further buffer strength losses at the fabric level. These measures are paired with contamination control (e.g., polyester stitch thread, labels) and weft-side allocation of lower-dye-affinity blends to stabilise dyeing outcomes. Emerging lab and pilot studies refine the same levers: controlled opener settings and gentler fibre-opening lines, coupled with quality-driven blending protocols, can preserve usable length distributions and deliver yarns that meet denim requirements. In fact, ring-spun yarns comprising $\geq 75\%$ mechanically recycled cotton have been demonstrated when fibre selection and spinning parameters are tuned, challenging the assumption that high recycled content is limited to rotor yarns (Kärkkäinen *et al.*, 2025).

Simultaneously, yarn and fabric engineering has diversified the solution space. Air-jet and rotor yarn structures can better tolerate short-fibre mixes, while compact ring and core-spun constructions (including elastic core yarns) can carry 40-60% recycled cotton and still reach top-quartile USTER (global textile quality standards) strength/elongation ranges, supporting commercial-speed weaving for denim weft. These architectures, together with coarser yarn counts and targeted blending with longer fibres (virgin cotton or recycled Polyethylene Terephthalate (rPET)), counteract strength deficits and reduce breakage in warping and weaving (Jabbar and Tausif, 2023; Uddin and Rahman, 2024). At fabric level, multiple evaluations of recycled-content denim report acceptable performance against minimum strength and serviceability thresholds, especially when process controls and weave design are leveraged, underscoring that mechanical recycling can support durable, mainstream denim stock keeping units (SKUs) rather than only down-cycled outputs (Karagöl *et al.*, 2024).

Finally, the literature emphasises that true circularity demands fibre-to-fibre pathways that are measurement-led (fibre length distribution, trash/contamination analytics) and integrated with sorting technologies tailored for cotton streams. Mechanical recycling will likely co-evolve with complementary innovations (e.g., lubricant-assisted tearing, hybrid spinning routes, selective blending, and traceability) to close quality gaps and stabilise supply of high-grade recycled cotton for denim. The 2024-2025 body of work therefore shifts the narrative from “down-cycling is inevitable” towards “process-and-design-led up-cycling”, provided mills instrument their recycling and spinning lines, enforce disciplined blending windows, and select yarn/fabric architectures that are inherently short-fibre tolerant (Islam *et al.*, 2025; Abteu *et al.*, 2025).

This review aims to critically analyse the challenges related to fibre quality degradation in mechanical cotton recycling for sustainable denim production. It also seeks to synthesise current and emerging strategies, including blending, chemical treatments, process optimisation, and advanced technologies, that address these issues to promote a more circular and sustainable textile industry.

CHALLENGES OF MECHANICAL COTTON RECYCLING

Recycled cotton fabric is a textile material made using cotton fibres recovered from pre-consumer waste (e.g., factory scraps) or post-consumer waste (e.g., old clothes) instead of using new, virgin cotton. The recycled cotton manufacturing process is presented in Figure 1.

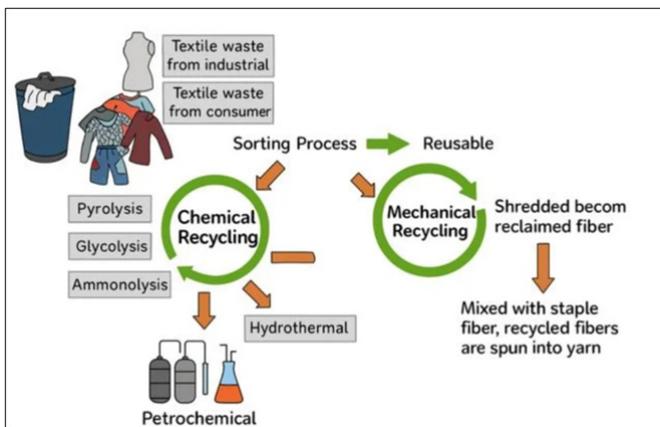


Figure 1: Recycled cotton manufacturing process

Source: <https://regenfabric.com/recycled-cotton-fabric-manufacturing-process>

The recycled cotton fabric manufacturing process involves collecting and sorting cotton waste, shredding it into fibres, cleaning and blending these fibres, spinning new yarn, and finally weaving or knitting it into fabric. This process often requires careful steps to maintain quality. Figure 1 illustrates the circular process of textile recycling, highlighting both mechanical and chemical routes. Textile waste generated from industrial and consumer sources undergoes a sorting process to separate reusable materials from those destined for recycling. In mechanical recycling, textiles are shredded into reclaimed fibres; these are then mixed with staple fibres and spun into yarn for new fabric production, maintaining the physical structure of the fibres. In contrast, chemical recycling involves breaking down textile waste through methods such as pyrolysis, glycolysis, ammonolysis, and hydrothermal treatment to regenerate the petrochemical raw materials used for producing new synthetic fibres (Peng *et al.*, 2024; Ma *et al.*, 2019). Together, these processes aim to minimise waste, recover valuable materials, and promote sustainability within the textile and fashion industries.

Mechanical recycling of cotton, while environmentally beneficial, presents several challenges that impact the quality of the resulting fibres and fabrics (Zhang *et al.*, 2023). The primary issue is the shortening of fibre length during the shredding and tearing processes. This reduction in fibre length directly correlates with a decrease in yarn strength and elongation, making the recycled fibres less suitable for high-quality textile applications (Anas *et al.*, 2025; Islam *et al.*, 2025; Ütebay *et al.*, 2019).

Research shows that using more than about 10% recycled cotton can greatly reduce yarn strength, elongation, and fabric durability. Fabrics with high recycled cotton content often have poor pilling resistance (Grade 1 vs Grade 4 for virgin blends). Mechanical recycling also recovers only 45-50% usable fibre from post-consumer denim, increasing losses, while contaminants, such as dyes and synthetics, further degrade yarn quality (Anas *et al.*, 2025). Mechanical recycling begins with sorting, cutting, and tearing denim waste into tufts, followed by opening, cleaning, blending, and carding to produce secondary fibres, as seen in Figure 2.

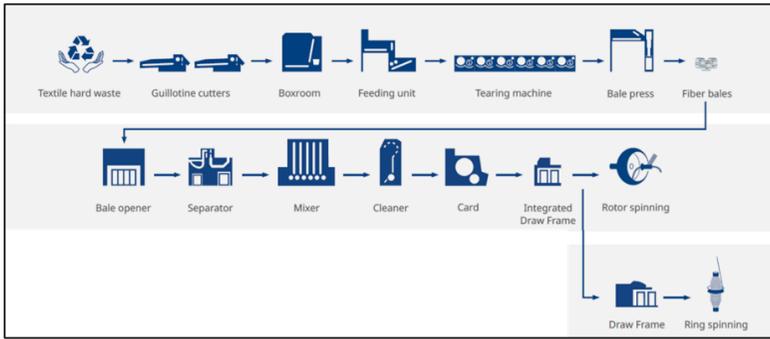


Figure 2: An Example of a State-of-the-art Recycling Process

Source: Trützschler Group SE

Figure 2 represents a closed-loop mechanical recycling system that transforms textile waste into new cotton yarns through sequential physical operations, without the use of chemical treatments. It ensures material recovery, resource efficiency, and alignment with circular textile manufacturing principles.

Studies show that the efficiency and quality of recycling depend heavily on machine design and process parameters. Kanan *et al.* (2024) developed a new opener with seven rollers (OP2), achieving 75% yield, 20.6% short fibre content, and 63.8% uniformity index, outperforming traditional two-roller openers. Trützschler’s TRUECYCLED® system integrates Balkan machinery to optimise fibre tearing and opening, minimising damage while enabling high-quality ring and rotor spinning from recycled materials. Despite these advancements, fibre degradation, mainly shortening and weakening during tearing, remains the key challenge, affecting yarn strength and spinnability.

STRATEGIES TO OVERCOME FIBRE QUALITY DEGRADATION

To enhance the quality and applicability of mechanically recycled cotton, several strategies are being explored and implemented (Table 1).

Table 1: Summary of the Key Challenges in Recycling Cotton

Challenge	Impact on Fibre Quality	Strategies to Overcome	Ref.
Fibre Shortening	Reduced yarn strength, elongation, and fabric durability	Blending with virgin cotton or other fibres (e.g., chemically recycled polyester)	Karmakar <i>et al.</i> , 2025; Anas <i>et al.</i> , 2025

Challenge	Impact on Fibre Quality	Strategies to Overcome	Ref.
Low Usable Fibre Yield	Increased processing losses, economic inefficiency	Optimisation of mechanical recycling processes (e.g., controlled shredding, tearing)	Anas <i>et al.</i> , 2025; Kanan <i>et al.</i> , 2024
Poor Fabric Performance	Low pilling resistance, reduced overall durability	Blending with virgin fibres, silicone softening treatments, advanced finishing techniques	Karmakar <i>et al.</i> , 2025; Anas <i>et al.</i> , 2025
Contamination (Dye, Impurities)	Affects physical appearance and quality of recycled yarns	Improved sorting technologies, targeted pre-treatments, hybrid recycling approaches (mechanical + selective chemical)	Anas <i>et al.</i> , 2025
Consistency Issues	Fibre length, strength, and colour vary between batches of recycled cotton, reducing uniformity of yarn and fabric.	Apply strict sorting and blending procedures; mix fibres from multiple waste sources to reduce variation; collaborate with suppliers that maintain strong quality control and provide fibre property test reports	Kanan <i>et al.</i> , 2022; Haq <i>et al.</i> , 2024
Limited Supply of High-Quality Post-Consumer Waste	Collection and sorting of post-consumer textiles are difficult, limiting the availability of high-quality recycled fibres compared to pre-consumer waste	Invest in textile collection and sorting infrastructure; form partnerships to ensure steady supply of sorted waste; support chemical recycling technologies that can handle mixed or complex waste streams	Li <i>et al.</i> , 2025; Haider <i>et al.</i> , 2025

Source: Constructed by authors based on literature review

This strategic combination of fibre blending, process optimisation, and supply-chain investment enables the effective use of mechanically recycled cotton while maintaining product quality and sustainability goals.

BLENDING WITH VIRGIN FIBRES OR OTHER MATERIALS

One of the most common and practical strategies to mitigate fibre quality degradation is blending recycled cotton with virgin cotton or other fibres. This approach helps to compensate for the shorter fibre length and reduced strength of recycled materials. Studies have shown that blending up to 75% cotton waste with virgin cotton can be achieved without significant degradation in the final fabric's quality (Karmakar *et al.*,

2025). Similarly, combining recycled cotton with chemically recycled polyester can improve the overall properties of the resulting yarn (Anas *et al.*, 2025).

Blending strategies prove essential for quality retention. Multiple studies show acceptable yarn quality with recycled content exceeding 50% (Kanan *et al.*, 2022), although fibre length reduction remains a key limitation (Haq *et al.*, 2024). Kärkkäinen *et al.* (2025) demonstrated that mechanically recycled denim fibres blended with virgin cotton (75/25 ratio) achieved promising tensile strength and acceptable abrasion resistance in single jersey knits. Haider *et al.* (2025) compared post-industrial and post-consumer waste in denim yarns. While both showed reduced fibre length and strength compared to virgin cotton, the resulting fabrics maintained acceptable performance levels for denim applications.

These findings show that fibre blending ratios, optimised spinning methods (such as rotor or ring spinning), and process improvements can mitigate some negative effects of fibre degradation.

CHEMICAL TREATMENTS AND PROCESS OPTIMISATION

While mechanical recycling aims to be chemical-free, targeted chemical treatments can be employed to improve fibre properties without fully resorting to chemical recycling. For example, a novel course mixing technique combined with a silicone softening treatment has been shown to elevate the quality of knitted fabrics made from recycled yarns (Karmakar *et al.*, 2025). Additionally, optimising the mechanical recycling process itself, by adapting it to the specific input material, can lead to improved fibre quality (Kanan *et al.*, 2024). This includes careful sorting, pre-treatment, and controlled shredding and tearing processes to minimise fibre damage.

Mechanical recycling of cotton textiles faces significant fibre quality degradation challenges, but research demonstrates several effective strategies to mitigate these issues through chemical treatments and process optimisation. Chemical treatments using cross-linking agents (citric acid with sodium hypophosphite) and polymers (starch, carboxymethyl cellulose) can enhance mechanically recycled cotton fibre tenacity by 4.6-4.9% while reducing yarn irregularities by up to 36% (Azevedo *et al.*, 2025). Process optimisation through improved mechanical design shows even greater promise, with seven-roller opener machines increasing yield by over 150%, mechanical properties by 5%, and fibre quality index by 9% compared to a two-roller system (Kanan *et al.*, 2024). Pre-treatment methods, including alkaline decolourisation and acid treatments for metal removal, prove essential for removing contaminants while preserving fibre structural integrity (Ribeiro *et al.*, 2025). However, chemical

recycling approaches demonstrate superior results, with ionic liquid dissolution methods producing regenerated cotton fibres with tenacity up to 58 cN/tex that exceed native cotton quality (Asaadi *et al.*, 2016; Schlapp-Hackl *et al.*, 2024). While mechanical recycling improvements are valuable for maintaining fibre utility in lower-grade applications (Cao *et al.*, 2022; Béchir *et al.*, 2018), the evidence suggests that chemical recycling represents the most promising pathway for producing high-quality recycled cotton fibres suitable for premium textile applications (Schuch, 2016; Abteu *et al.*, 2025).

ADVANCED TECHNOLOGIES AND INNOVATIONS

Innovations in textile recycling technologies are continuously emerging to address fibre quality issues. These include:

Feedstock-agnostic recycling technologies (Figure 3)

Companies such as RE&UP are developing solutions that can process various types of textile waste to create high-performance, ready-to-use, traceable next-generation fibres.

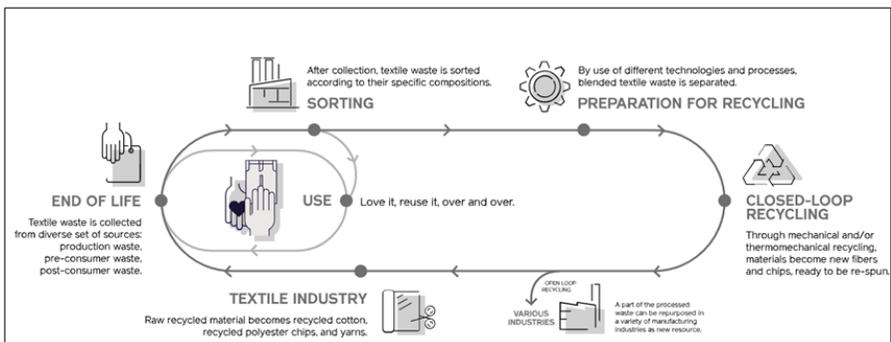


Figure 3: The One-Stop Solution Provider

Source: <https://reandup.com/what-we-do/>

Fibre reinforcement

Ongoing research focuses on methods to reinforce recycled cotton fibres, potentially through bio-based additives or structural modifications, to enhance their strength and elasticity.

Hybrid approaches

Combining mechanical recycling with selective chemical treatments or advanced sorting technologies can lead to higher quality recycled fibres, bridging the gap between purely mechanical and purely chemical methods.

ADVANCED MACHINERY FOR GENTLE PROCESSING OF DENIM FABRIC

Advanced machinery for gentle denim processing includes nano-bubble technology, stone-free systems, aerosol processing, and ultrasonic treatment methods that significantly reduce environmental impact while maintaining fabric quality.

The evidence shows strong support across multiple technologies. E-flow nano-bubble technology achieves soft hand feel with minimal water and zero discharge (Khalil, 2016). No Stone technology eliminates pumice stones while reducing water consumption and carbon footprint (Nahid-Ull-Islam *et al.*, 2024a). Aerosol technology demonstrates substantial resource savings: 75% water reduction, 47% energy savings, and 80% salt reduction at commercial scale (Wahab and Hussain, 2020). Ultrasonic processing at 25kHz/300W achieves desired fading without material degradation (ben Ticha and Meksi, 2022). Single-bath enzymatic treatment produces four times less wastewater oxygen demand than conventional methods (Islam *et al.*, 2024). However, the evidence is primarily from individual case studies and pilot implementations rather than large-scale comparative trials, limiting generalisability across different denim processing facilities.

Modern denim processing technologies, such as laser finishing, ozone washing, enzymatic washing, and E-Flow nano-bubble technology, provide gentle, sustainable alternatives to traditional methods such as stonewashing and sandblasting. These advancements improve efficiency and environmental performance by reducing resource use and minimising fibre damage. More about these technologies can be found in various industry and research sources (e.g., Venkatraman, 2022; Sarkar *et al.*, 2022; Kamppuri and Mahmood, 2019; Faria and Shakey, 2025; Sarker *et al.*, 2021; Patra *et al.*, 2018; Hasan *et al.*; Zouari *et al.*, 2023). Figure 4 provides a visual comparison of the environmental and quality impacts of traditional versus sustainable denim finishing methods.

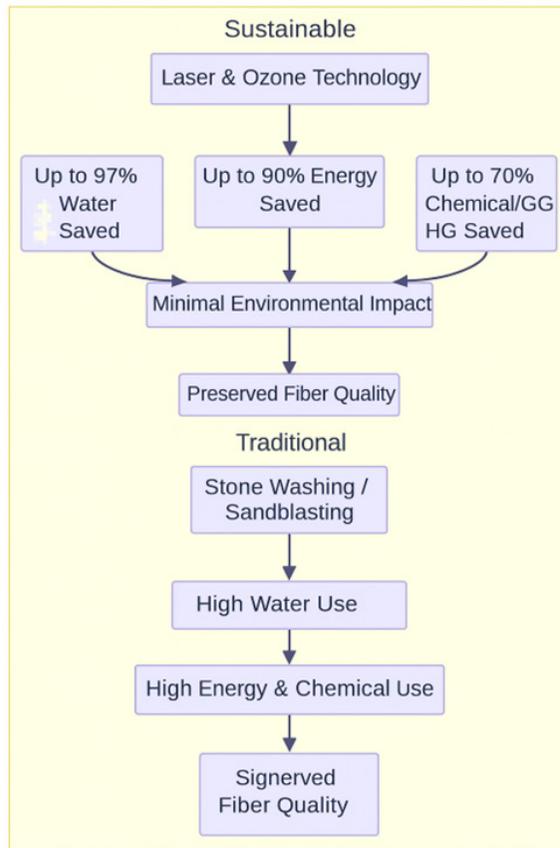


Figure 4: Comparison of Traditional vs Sustainable Denim Finishing Methods (Laser and Ozone)

Source: Nayak *et al.*, 2022, Nahid-Ull-Islam *et al.*, 2024b

Compared to traditional processes, modern techniques achieve up to 97% water savings, reduce chemical use with natural agents such as enzymes and ozone, and preserve fabric strength by avoiding harsh mechanical wear. Laser finishing employs CO₂ lasers to selectively vaporise indigo dye without touching the fabric, resulting in a chemical-free and damage-free finish. Ozone washing uses O₃ gas in sealed chambers as an oxidising agent, allowing about 60% less water use and faster cycle times. Enzymatic washing utilises cellulase enzymes to gently break down surface cellulose, providing a biodegradable and fibre-friendly alternative. The E-Flow technology, the latest innovation, uses nano-bubbles to carry concentrated chemicals in a fine mist, leading to 95% less water use and lower energy consumption (Figure 5).

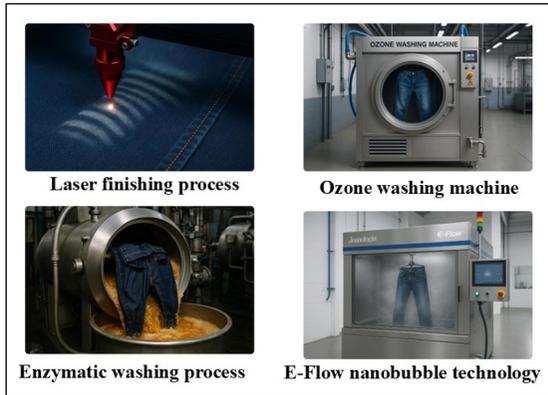


Figure 5: Advanced Machinery for Gentle Processing of Denim Fabric

Source: Constructed by the authors based on the company's website, Jeanologia, Tonello S.r.l, Jeanologia, and IFF

These sustainable finishing technologies not only enhance precision and process control but also support the denim industry's transition towards eco-friendly production. According to leading manufacturers such as Jeanologia, Tonello, GBOS, and Ozon Denim, these methods are now integral to next-generation denim manufacturing systems. The comparative data (Figure 6) highlight a dramatic decline in water consumption, with E-Flow systems achieving up to a 95% reduction compared with traditional methods, marking a paradigm shift towards sustainable, digitally controlled denim processing.

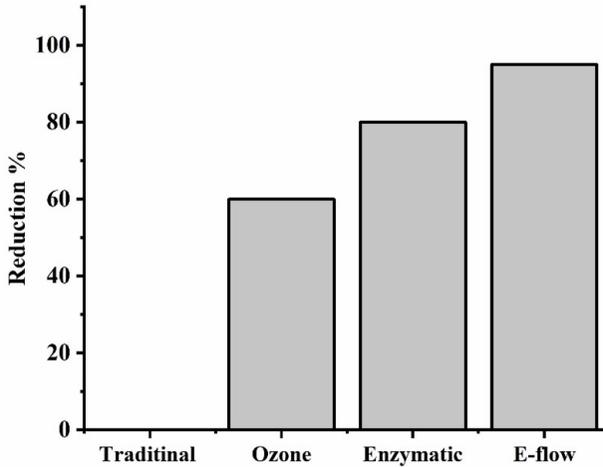


Figure 6: Water Reduction Compared to Traditional Processing

Source: Constructed by authors based on literature review

INDUSTRY INITIATIVES AND COMPANIES

Multiple research initiatives are actively advancing mechanical cotton recycling and sustainable denim production through innovative recycling techniques and technological improvements.

Researchers have demonstrated significant progress in mechanical cotton recycling, with studies showing the ability to incorporate up to 60% recycled cotton in yarn production (Uddin and Rahman, 2024; Habib *et al.*, 2024). These efforts have yielded promising results, including improved yarn characteristics and potential environmental benefits. For instance, life cycle assessments reveal substantial reductions in resource depletion, global warming potential, and water use when using recycled cotton (Karagöl *et al.*, 2024).

Key innovations include advanced opener machines that can increase fibre yield by over 150% and improve fibre quality (Kanan *et al.*, 2024). While challenges remain in maintaining fibre length and quality, the research demonstrates a strong commitment to developing sustainable textile recycling methods.

Several companies and initiatives are actively working to advance mechanical cotton recycling and promote sustainable denim production (links to the company webpages can be found in the reference list):

- **Blue Jeans Go Green™:** This programme, supported by Cotton Incorporated, collects denim made from at least 90% cotton to divert textile waste from landfills and convert it into new materials, such as building insulation.
- **Candiani Denim:** Known for its commitment to sustainability, Candiani Denim actively incorporates recycled cotton and innovative technologies to produce eco-friendly denim fabrics.
- **RE&UP:** This company focuses on developing advanced recycling technologies that can handle diverse textile waste streams, aiming to produce high-quality recycled fibres for various applications.
- **Circular Fashion Partnership:** A cross-sectoral initiative led by the Global Fashion Agenda that includes partners such as Recover™. It aims to scale textile-to-textile recycling by facilitating collaborations between manufacturers, recyclers, and brands.
- **Textiles 2030:** A UK-based initiative run by the Waste and Resources Action Programme (WRAP). It supports businesses in transitioning to circular practices with science-based targets for carbon and water footprint reductions.
- **Global Recycled Standard (GRS):** This certification, owned by Textile Exchange, verifies the recycled content and tracks the flow of recycled materials through the supply chain. It also sets strict environmental and social requirements.
- **Recover™:** A global producer of recycled cotton fibre and blends, Recover™ provides materials to brands such as Primark, Revolve, and C&A. Their proprietary RColorBlend system creates new, coloured fibres by mixing their recycled cotton with other low-impact dyed fibres, eliminating the need for further dyeing. Recover™ is certified under GRS and OCS.
- **Patagonia:** Known for its long-standing commitment to sustainability, the Patagonia company uses recycled materials, including mechanically recycled cotton, in products such as its Responsibili-Tee that blends recycled cotton and recycled polyester.
- **Levi Strauss & Co.:** Through its “WellThread” collections, the brand has integrated mechanically recycled cotton and has invested in research for new recycling technology with partners such as the Massachusetts Institute of Technology (MIT).
- **H&M Group:** The company features mechanically recycled cotton in its “Conscious Collection” as part of its goal to use only sustainable materials by 2030.

- **Inditex (Zara):** Inditex is committed to using 100% sustainable materials, including recycled fibres, across all of its brands by 2025.
- **G-Star RAW:** This denim brand uses recycled cotton in its collections, including initiatives such as the “RAW for the Planet” campaign, to promote circularity in the denim industry.
- **Ecoalf:** A Spanish fashion brand that focuses on using recycled waste as its raw material. It launched a 100% recycled cotton collection in 2023.
- **Kings of Indigo:** This denim brand uses GRS-certified recycled materials, including cotton, as part of its “Triple R” principle: Repair, Reuse, and Recycle.
- **Birla Cellulose:** Launched Liva Reviva™ M, a man-made cellulosic fibre made with up to 50% mechanically recycled post-consumer textile waste (Cellulose).

Overall, both academia and industry are demonstrating a strong commitment to advancing sustainable textile recycling technologies and reducing the environmental footprint of denim production.

CONCLUSIONS

Mechanical cotton recycling is indispensable for fostering a sustainable textile industry, significantly reducing environmental impact and conserving resources. Despite persistent challenges related to fibre quality degradation, this review demonstrates that substantial progress is being made through a combination of strategic interventions. Key strategies, including intelligent blending with virgin fibres, judicious application of chemical treatments, and the continuous development of advanced recycling technologies, are proving increasingly effective in mitigating these limitations. The future of sustainable denim production hinges on the continued collaborative efforts of researchers, innovators, and industry stakeholders. By embracing these multi-faceted approaches, the textile sector can accelerate its transition towards a truly circular economy, ensuring both environmental stewardship and the production of high-quality recycled materials.

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BIOGRAPHY



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Dr Ramadan Mohammed is an Associate Professor in the Department of Textile Engineering at the Sudan University of Science and Technology, and an affiliated researcher at Istanbul Technical University, Türkiye. He received his PhD in Textile Composites from Donghua University, China, where his work concentrated on the development and characterisation of advanced fiber-reinforced composite materials. His academic and research interests include high-performance textile composites, smart and sustainable materials, circular textile economy, and the integration of novel fabric architectures for structural and functional applications. Dr Mohammed has contributed to numerous peer-reviewed publications and international conferences, and he actively promotes cross-border research collaboration between Africa, Asia, and Europe in the field of textile innovation and sustainability. He also supervises postgraduate research in materials science and textile engineering, focusing on advancing environmentally responsible technologies for the textile and composite industries.



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